J/ψ Polarization at 800 GeV Proton-Copper Interactions

Vassili Papavassiliou, NMSU

Feb. 24, 2000

Outline

- ✔ Motivation
- ✔ Theory
- ✔ Experiment
- ✔ Implications

Presented at the 2nd Workshop on B Physics at the Tevatron: Run II and Beyond

Motivation

J/ψ Production still not very well understood

Why is this process important?

- *Charm* production reasonably well explained by QCD
  charm quark mass large enough for perturbative calculations, yet small enough for copious production at fixed-target experiments

- *Charmonium* production more complicated
  $c\bar{c}$-pair binding is long-distance effect — not calculable in pQCD

- Effective Field Theory: Non-Relativistic QCD
  $c\bar{c}$-pair does not need to be in color-singlet state to form charmonium

- Relative magnitude of **color-octet** and **color-singlet** matrix elements not fixed by theory
  must be determined from experiment (*e.g.* fit to total production cross section)

- Still, significant predictive power
  ME's determined from some process can be used to predict another

Charmonium production provides important tests of QCD

Charmonium Production in NRQCD

Basic parton processes for *direct* production ($H = \psi, \chi_J$):

- $gg \to c\bar{c} \to H$
  $c\bar{c}_8$
- $q\bar{q} \to c\bar{c} \to H$
  $c\bar{c}_8$
- $gq \to c\bar{c}q \to H$

Both $2 \to 2$ and $2 \to 3$ processes contribute

Intermediate $c\bar{c}$ state can be color-octet or color-singlet

Respective ME's: $\mathcal{O}_8^H(^{2S+1}L_J)$ and $\mathcal{O}_1^H(^{2S+1}L_J)$

Actual number of independent matrix elements is smaller due to spin-symmetry relations

$$e.g. < \mathcal{O}_8^{\psi}(^3P_J) >= (2J+1) < \mathcal{O}_8^{\psi}(^3P_0) >$$

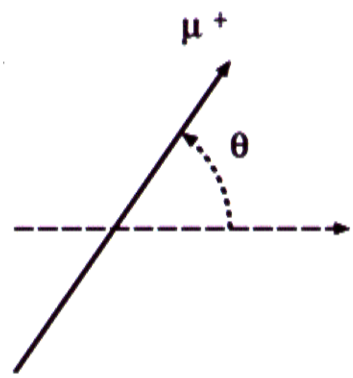
Several combinations of ME's derived from fits to total cross sections

Predictions of polarization should come "for free"

Polarization assumed to survive soft-gluon radiation in FS

Measurement

Polarization measured through angular distribution of direction of dimuon vector in charmonium center-of-mass frame



$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda\cos^2\theta$$

λ	Polarization
> 0	Transverse
$= 0$	Unpolarized
< 0	Longitudinal

Note: *θ can be measured either with respect to the beam direction or to the bisector of the angle of the two initial-state hadrons*

Difference negligible at small p_T

Predictions

- Transverse ψ polarization expected at large p_T
  Production dominated by gluon fragmentation
  Not seen in CDF data

- Mostly transverse ψ polarization at fixed-target energies
  Expect $0.15 < \lambda < 0.44$ (Beneke and Rothstein)
  Also not in agreement with experiment
  — Very little or no polarization seen
  But: averaging over x_F may be masking some effects
  Need to study x_F dependence with high statistics

Complications

1. There is more than just the direct production
   J/ψ can be the product of ψ' or χ_c decays
   All charmonium states can be products of b decays
   Inclusion of χ_c decays increases *the polarization*

2. Relative importance of gg and $q\bar{q}$ terms varies with x_F
   $q\bar{q}$ dominates at large x_F, gg everywhere else

3. Nuclear effects at fixed-target experiments could affect singlet and octet states differently
   Nuclear effects known to be strongly x_F-dependent

Note: *At fixed-target energies gluon fragmentation is much less important (not high-enough p_T) and b decays are negligible*

The Experiment

FNAL E-866/NuSea Experiment

Dimuon-production in 800-GeV p interactions

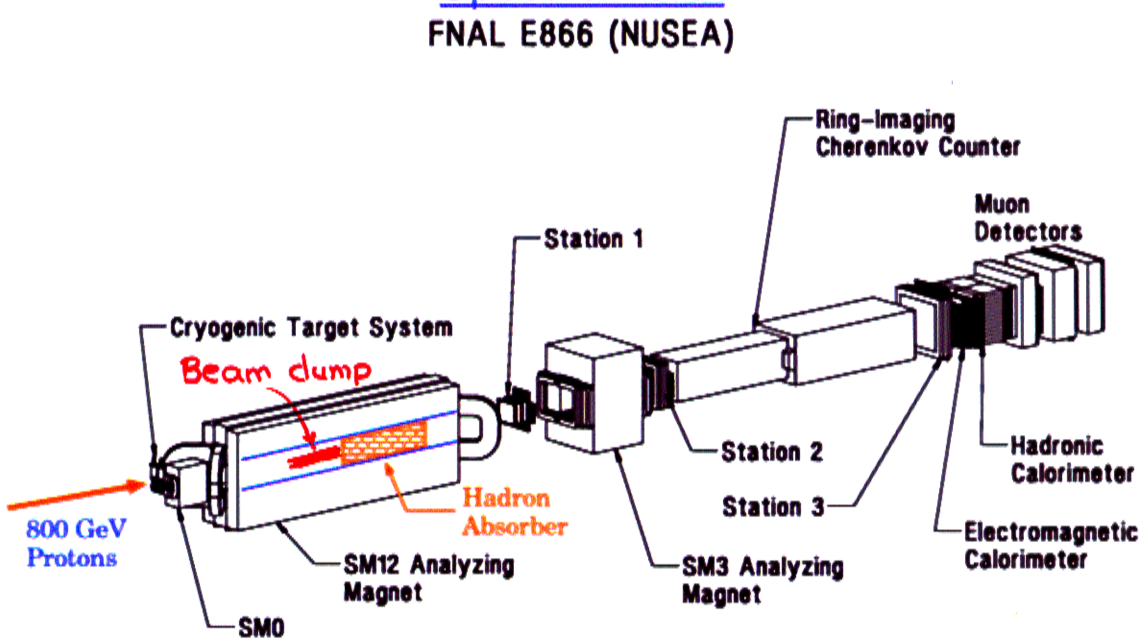
with various targets (H_2, D_2, Be, Fe, W)

Both Drell-Yan and quarkonium production studied

Main motivation: study the **Nucleon Sea** ($\bar{d}/\bar{u}$ ratio)

Also: nuclear effects in dimuon production

Spectrometer



Angular Distribution Data

Dedicated run in April '97 using the beam dump as target

✔ High statistics data with acceptance centered around the J/ψ peak

- 400M triggers recorded in three weeks
  — mostly ψ's; some Drell-Yan continuum and random pairs from charm decays
- Frequent configuration changes to study biases
  — two different magnet currents
  — two opposite polarities

✘ Degradation of mass and vertex resolution

- J/ψ and ψ' peaks cannot be separated
  $\sim 1\%$ contamination from ψ'
- Monte Carlo corrections for energy loss and multiple scattering without benefit of "point" target

Also, acceptance not uniform as a function of θ

Again, rely on Monte Carlo for correction

Analysis

Doctoral dissertation of Ting-Hua Chang (NMSU)

- Dimuon mass reconstructed from extrapolated vertex position

- Corrections for energy loss and multiple Coulomb scattering

- Mass spectrum fitted to Gaussian plus background in θ, x_F and p_T bins

- Event yields from fits plotted versus θ

- θ distributions divided by corresponding Monte Carlo ones, generated flat in θ (*i.e.* unpolarized)
  $\Rightarrow$ Obtained acceptance-corrected θ distributions

- Corrected θ distributions fitted to $N(1 + \lambda \cos^2 \theta)$ to obtain polarization λ in x_F and p_T bins

$\Longrightarrow$ *About 10^7 J/ψ events left in the final data set*

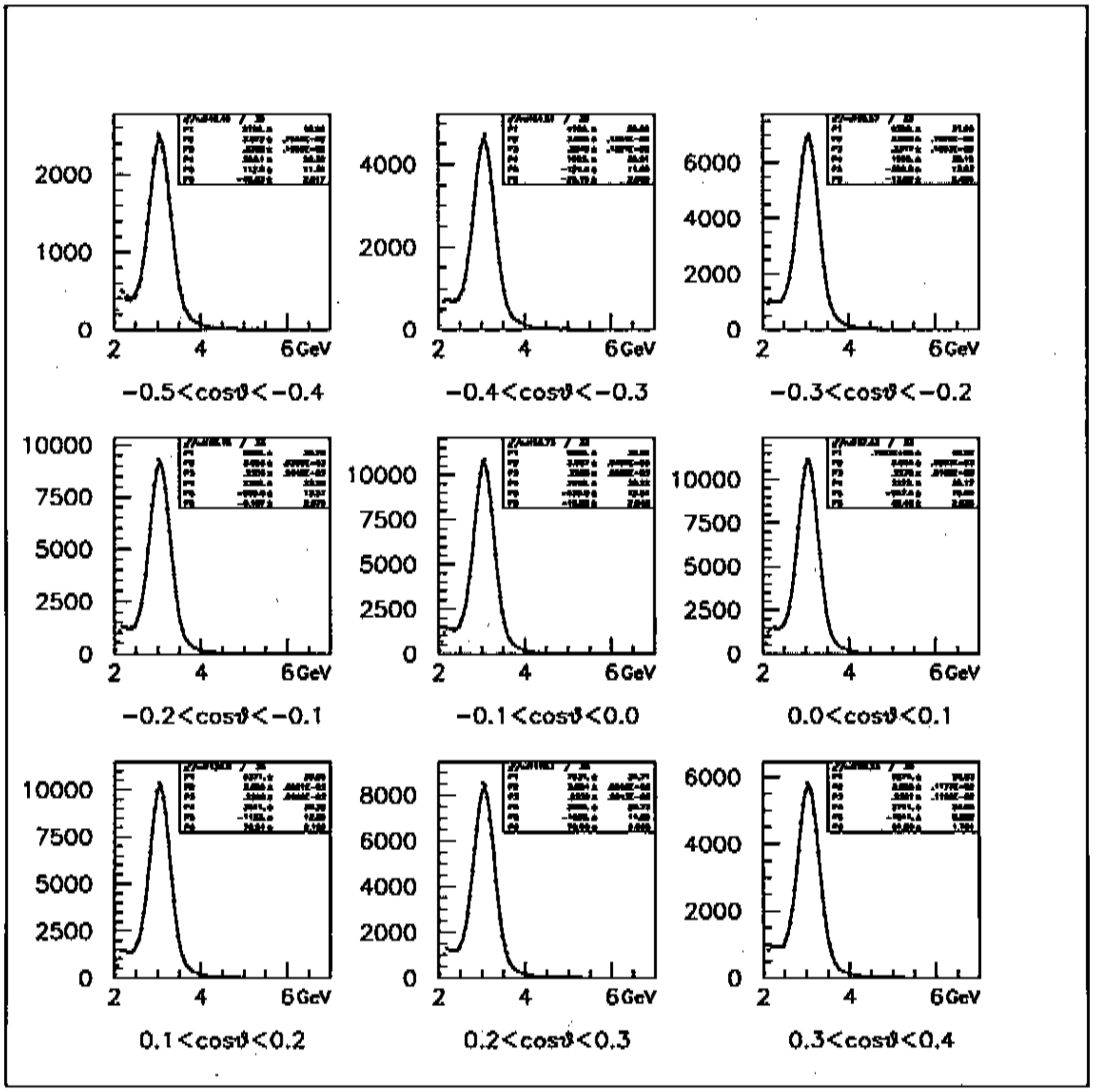


Figure B.1: Fitting of the mass spectrum: $0 < p_t < 1$ and $0.25 < x_F < 0.35$. The backgrounds were fitted to second-order polynomials, and the J/ψ's were fitted to Gaussians. The $\cos\theta$ ranges are indicated under each spectrum. The current of SM12 magnet was 2040 Ampere.

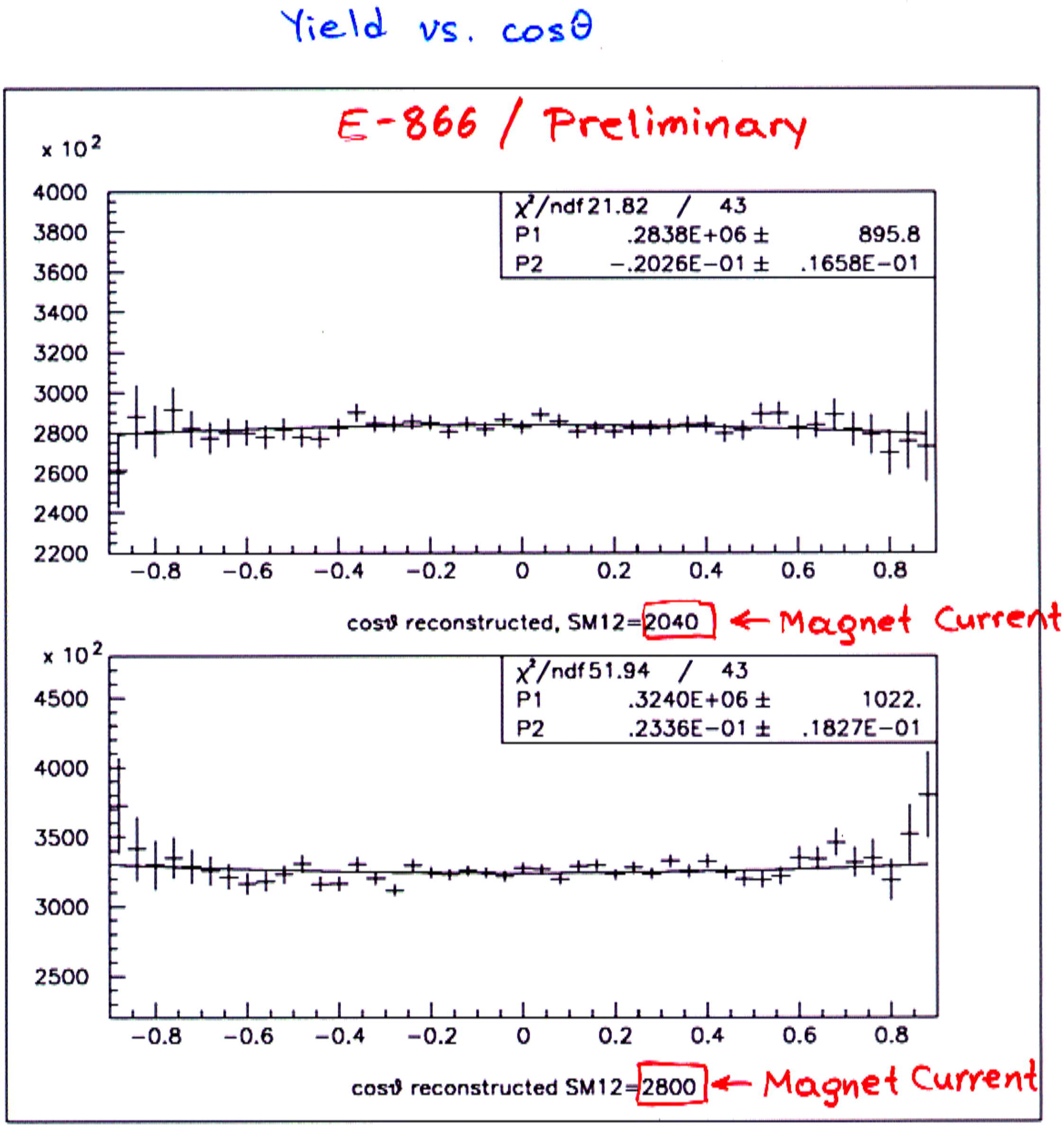


Figure 3.2: Reconstructed $\cos\theta$ distributions for both magnet settings. The reconstructed distributions recover the thrown (flat) distributions.

Polarization vs. P_T in two X_F regions

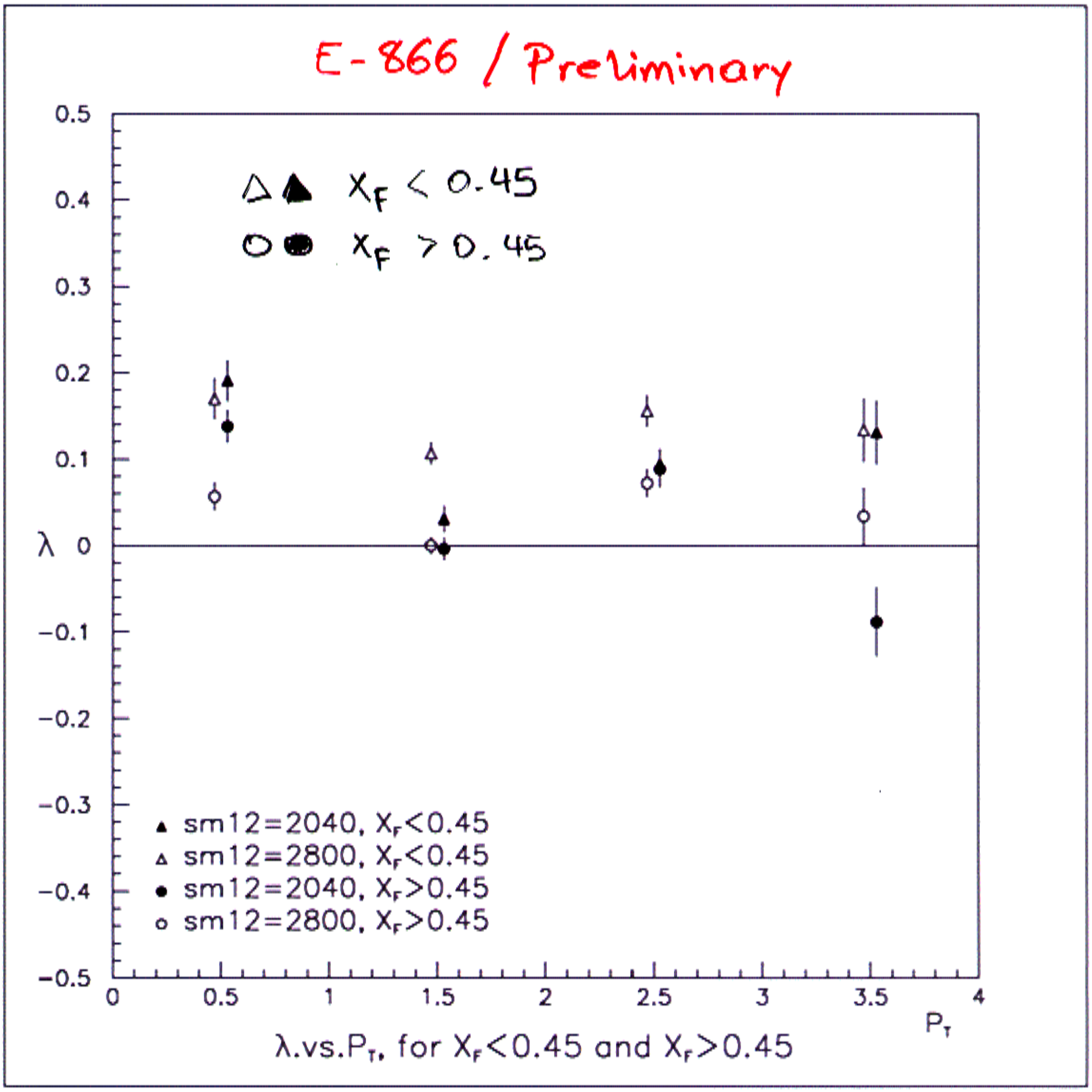


Figure 5.7: J/ψ polarization parameter λ in 1-GeV p_T bins. The plot shows λ in two regions of x_F: $x_F < 0.45$ and $x_F > 0.45$. The errors are statistical only.

Polarization vs. x_F — Integrated over p_T

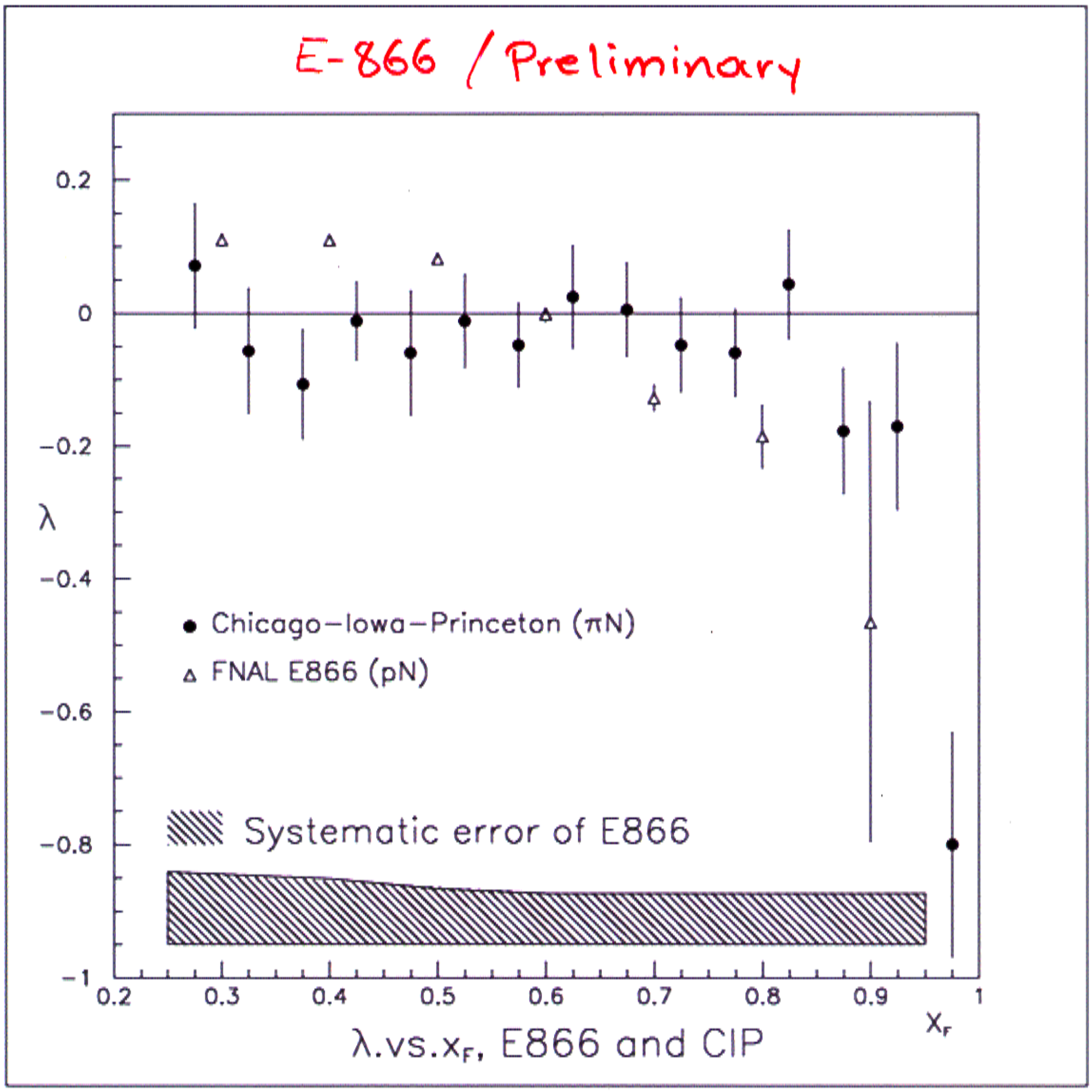


Figure 5.6: $\lambda(x_F)$ from FNAL E866 and from CIP group. The error bars on E866 data are statistical only; the systematic error is shown in the shadowed band below.

Systematic Uncertainties

The following sources of systematic errors were considered:

- Incoming beam angle
- Beam centroid
- Shape of assumed $d\sigma/dp_T$
- Limits of fits
- Backgrounds
- Magnet currents

Overall systematic uncertainty $\sim \mathcal{O}(10\%)$
— with little x_F dependence

Cross Checks

Several tests increase confidence in results

- Results from different magnet polarities and fields in reasonable agreement with each other

- Angular distribution for Drell-Yan above J/ψ peak consistent with 100% transverse polarization, as expected
  After subtraction of background from random coincidences of unrelated muons

- Checked sensitivity to shape of background under J/ψ peak, p_T shape of assumed production cross section, *etc*

All the above are included in the systematic errors cos θ distribution — Drell-Yan events (M > 4 GeV)

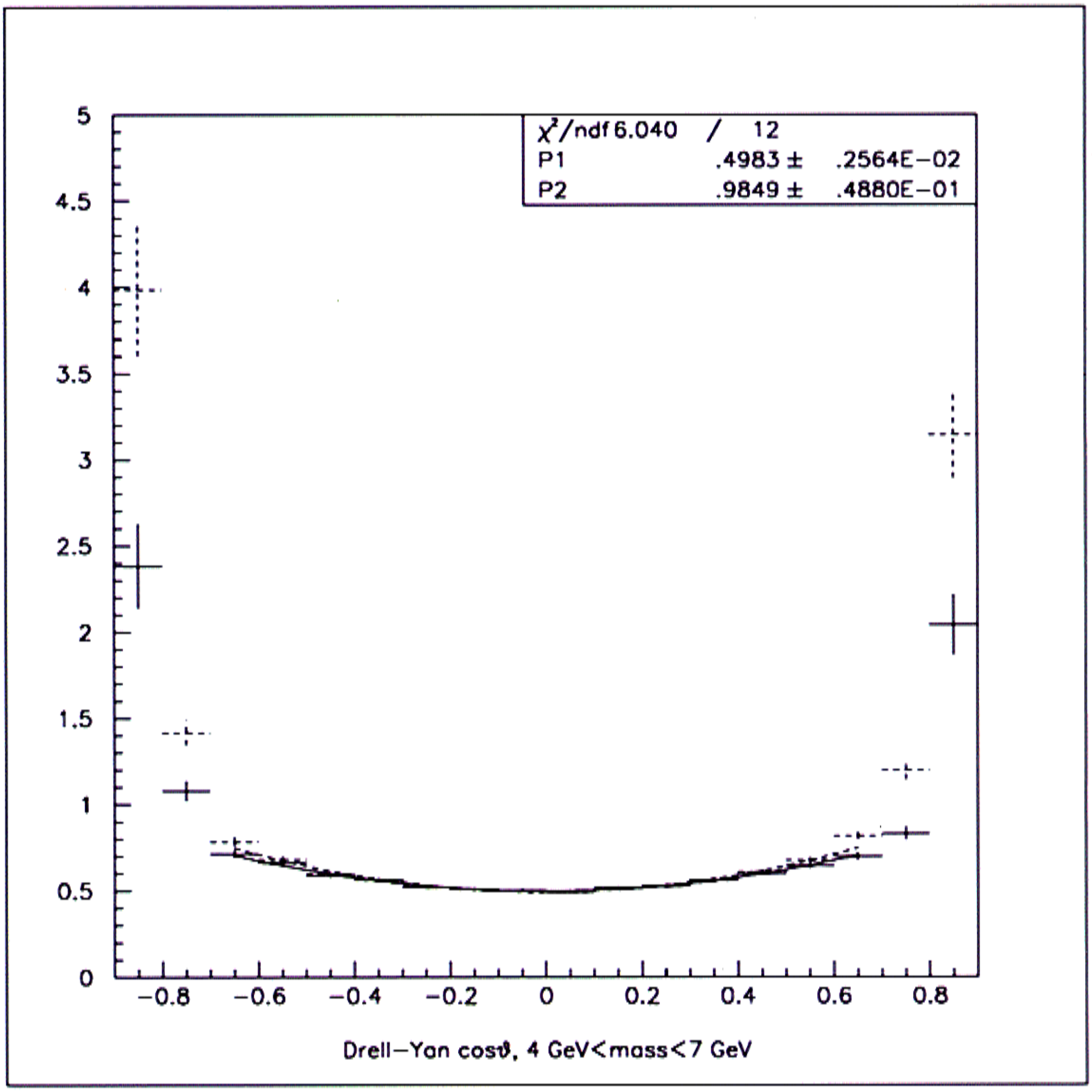


Figure 5.3: cos θ of the Drell-Yan pairs. The pairs have mass ranging from 4 GeV to 7 GeV. Solid line: After random subtraction. Dashed line: Before random subtraction. A λ value of 0.98 ± 0.04 is obtained after correcting for the random pairs. The rise at the edges is due to resolution effects.

Discussion

Highest-statistics measurement of J/ψ production polarization to date

- Integrated over x_F, the J/ψ is produced essentially unpolarized
- Small transverse polarization may be seen at small-to-medium x_F
  Consistent with zero when systematic errors are taken into account
- At large x_F polarization turns to longitudinal
  Similar effect seen with pion beams
- Polarization largely independent of p_T from 0 to 4 GeV
- Polarization change roughly coincides with transition from gg to $q\overline{q}$ dominance of the cross sections
  High x_F region may be dominated by higher-twist effects
  Effect of χ_c decays must also be considered

$\Longrightarrow$ *Understanding the details of charmonium production requires more work*

Implications

In addition to its significance in improving understanding of QCD in the long-distance regime:

Understanding the details of charmonium production is also important for RHIC — in particular the spin program

- J/ψ production through gluon-gluon fusion one of the best hopes to pin down contribution of gluons to proton spin — potentially very large

- Production asymmetry depends on relative magnitude of various matrix elements — different angular momentum as well as color

- Most calculations to date done in the color-singlet model, known to be incapable of describing magnitude of total cross section

$\Longrightarrow$ *Need updated calculation using right mix of matrix elements — when we know them!*